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THE EFFECTS OF CHANGES IN FORMATION PERMEABILITY AROUND THE WELL BORE ON THE PRODUCTION BEHAVIOR OF A WELL

William Nahmen Paulsen

THE EFFECTS OF CHANGES IN ATMOSPHERIC PRESSURE
AROUND THE HEAD AND ON THE TYMPANIC
MEMBRANE OF A CAT

74

by

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Submitted to the Graduate Faculty of the University
of Pittsburgh in partial fulfillment of the
requirements for the degree of
Master of Science

University of Pittsburgh

1965

The author wishes to express his appreciation to Professor Wolfgang G. Knauss, Head of the Aeronautics Engineering Department, University of Pittsburgh, for his helpful suggestions and comments in the preparation of this report and to the U. S. Naval Post Graduate School, Monterey, California, through whose sponsorship this paper was made possible.

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1. INTRODUCTION

The process of removing oil from a reservoir and the rate at which it may be produced depends on the physical characteristics of the reservoir rock and the properties of the fluids contained therein. Reservoir Engineering, the science of the production of oil from a reservoir formation, has been developed within the last thirty years. During this period extensive laboratory research has been conducted to ascertain the physical composition and properties of the fluids contained in the reservoir and the relationships that describe their flow through the reservoir formation at the prevailing temperatures and pressures. Many empirical models have been presented to describe the flow of these reservoir fluids both quantitatively and qualitatively.

If two non-mixing fluid (or a multiple permeable formation which is completely saturated with a certain fluid) the equations of flow are relatively simple. But a condition of varying permeability with non-permeable fluid flow the differential analysis becomes complicated. Finally, for a formation which contains three phases (water, oil and gas) the differential analysis becomes extremely complex. Recent by approximation or the mathematical analysis have been made for practical applications in three-phase flow cases.

In 1856 Henry Darcy carried out the study of linear flow of a fluid through a permeable medium contained and the first was directly proportional to the pressure difference between the two points of flow and inversely proportional to the fluid viscosity. This constant of proportionality was termed "permeability" and was defined as "a

measure of the property of the porous medium to permit flow of a fluid through its interconnected pores.[1] The unit of permeability is the "darcy" and is defined as "the rate of flow in milliliters per second of a fluid having a viscosity of one centipoise, through a cross section of one sq. cm. of the rock under a pressure gradient of one atmosphere per centimeter, and conditions of viscous flow."[2] This relates to the fundamental relationship upon which the principles of fluid flow are based.

In 1859, the famous Drake oil well was completed at Titusville, Pennsylvania, which started the story that a well was specifically drilled for oil in the United States. The rule for oil was an exception until wells were drilled with reliable degrees of success.

During the early 20th century production was placed on exploration instead that with little regard for improvement in completion methods, production techniques, and recovery. As a result, wells were damaged beyond repair and millions of barrels of oil were irretrievably lost.

As more and more wells were brought in and the demand for oil grew, more interest was directed to the factors which increased the flow of oil through the reservoir to the well. Laboratory investigations were undertaken and mathematical analyses were made to determine the physical characteristics of the oil and the conditions of flow which would maximize the recovery of the oil in the reservoir during the productive process.

In 1937 M. Muskat published an exhaustive study on the mathematical analysis of fluid flow entitled "The Flow of Homogeneous Fluids

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[1]References are listed in the Bibliography.

IV. STATEMENT OF THE PROBLEM

Numerous books, articles, and technical papers have been written to describe the flow of fluids through a reservoir during the production process. Equations have been developed and graphical interpretations have been drawn to represent the instantaneous rate of flow of fluid through a reservoir to a producing well under varying conditions of the reservoir and of the [illegible] flow. Methods have also been developed to estimate the total potentially recoverable reserves of petroleum in a reservoir under varying types of production drives and production methods. The most important single factor to be considered in determining the production rate which can be expected to be handled during the life of the well is the effective permeability of the formation to the oil. While the formation is wholly saturated with oil (less connate water saturation) the effective permeability is synonymous with the formation permeability. However, if gas, water or [illegible] is [illegible] in the oil [illegible] out of solution during production, the oil saturation will decrease and the effect is to reduce the effective permeability of the formation to oil which will result in proportionately less oil in the flowing stream for a given pressure gradient. This paper will be restricted to the flow of a single homogeneous fluid.

Formation permeability depends on the cross-sectional area and tortuosity of the paths in the formation through which the fluid flows. These properties depend on the grain size distribution, type of packing, and degree of cementation. Formations which contain clay may have a

damage caused permeability near the well bore due to invasion and the drilling and construction fluid into formation, thereby reducing the flow of fluid and gas from the formation. Induced permeability can also be caused by cracking of the formation by improper completion procedure during well completion. Consequently the permeability around the well bore may be considerably increased over that of the remainder of the formation in producing wells effectively increasing the radius of the well bore by many times.

Because of the possible differences of a well and greatly varied of the adjacent formation, the well bore is the main boundary of the drainage area. It should be noted that for a low permeability well with small or no fracturing of the formation, most of the pressure drop occurs near the well bore. Because of this, any change of the formation permeability around a small distance of the well bore substantially affects the production rate.

The formation may naturally have an extensive net degree of damage of permeability around the well bore compared to the permeability of the formation away from the well bore in the producing oil-bearing zone. This damage can be derived the reservoir pressure, the formation permeability near the well bore, and the degree of change of formation permeability around the well bore.

The purpose of this paper is to develop additional practicable procedure and equations to permit the accurate determination of the extent of permeability around the well bore and of the productivity of the well. An additional purpose is the easy evaluation of permeability of damaged formation around a producing well, and the procedure whereby such may be determined.

III. METHOD OF THE THEORY OF RADIAL FLOW

CHAPTER I FUNDAMENTAL THEORY

§ 1. The following brief general outline will serve to review the "Flow of Compressible Fluids Through Porous Media."

a. Radial Fluid Flow of a Single, Non-Compressible Fluid Through a Uniformly Permeable Medium[2]

The basic equation of flow is the Laplace equation:[3]

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) = 0 \qquad (1)$$

The required solution to this form of equation is:

$$p = A_1 \ln r + A_2 \qquad (2)$$

where A_1 and A_2 are constants of integration

In accordance the conditions

$$p = p_w \quad \text{when } r = r_w$$

$$p = p_e \quad \text{when } r = r_e$$

Substituting these values into equation (2) the specific solution to equation (1) is:

$$p = p_w + \frac{p_e - p_w}{\ln r_e/r_w} \ln r/r_w \qquad (3)$$

The velocity potential $= \frac{k}{\mu} p$

Therefore the radial velocity $(v_r) = \frac{k}{\mu}\frac{\partial p}{\partial r}$

---

[2] Symbols and abbreviations are listed in Table I of the Appendix.

Wall Thickness	$\frac{\Delta L}{L \cdot \Delta T}$	Wall Thickness	$\frac{\Delta L}{L \cdot \Delta T}$
1000	1×10^{-6}	1750	2×10^{-7}
1100	$\_\_^{-6}$	1760	10^{-6}
1200	$\_\_^{-6}$	1800	10^{-6}
1300	$\_\_^{-6}$	1850	10^{-6}
1400	1.5×10^{-6}	1900	10^{-7}
1500	1×10^{-6}	1960	5×10^{-8}
1600	1.5×10^{-6}	2000	2.5×10^{-8}

Solution:

1. Plot wall thickness versus $\frac{\Delta L}{L \cdot \Delta T}$ on semi-logarithmic paper. This relationship can be found in the literature as Figure 7.

2. Determine the average wall thickness of the building material as $\frac{\Delta L}{L \cdot \Delta T} = 10^{-6}$. Use the average allowable pressure (p_a) = 1210 psi.

3. Determine the temperature difference between the wall surfaces (ΔT = 90 degrees F).

$$t = \frac{r(p_i - p_o)}{S} = \frac{(\quad)(\quad)}{(\quad)(\quad)} = \quad \text{in.}$$

4. Determine the heat flow $q = \frac{\Delta L}{L} \cdot \frac{1}{R}$ (use $\Delta L = 1$)

Solve problem 2

$$\frac{\Delta L}{L \cdot \Delta T} = \frac{(\Delta L)_2}{(\quad)(\quad)} = \frac{(\quad)(\quad)(\quad)(\quad)}{(\quad)(\quad)(\quad)(\quad)}$$

$$= \quad \times 10^{-7}$$

[illegible equation]

Where:

r_e = 33 feet = 396 inches

r_w = 3.25 inches

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Substituting the above values into the equation and solving:

[illegible]

Summary:

From a study of [illegible], the following conclusions and recommendations:

1. It is of great importance to determine as soon as possible in the [illegible] whether there is a change of permeability of the formation [illegible]. If the permeability of the formation [illegible], the production rate will be reduced [illegible] the life of the well.

[illegible] should be [illegible] as soon as possible after [illegible] so that the various factors affecting [illegible] the well can be determined.

2. If the permeability of the formation around the well bore is found to be appreciably lower than that of the surrounding formation,

5. Effect of selected reservoir data on the economically recoverable reserves

The estimate of recoverable and economically recoverable reserves of a reservoir is quite sensitive to changes in many variable factors including gas price, cost of drilling and operating the reservoir, gas composition and personal considerations of the investor. Cut-off limits (oil, water and gas), gas relative permeability curves, gas production rate, and the type of displacement drive. It is therefore the scope of this paper to go into a detailed discussion of these factors. However, it would be reasonable the application of the principles learned, the types of displacement drives will be discussed in brief, and an illustrative example presented for each type to give the reader an intuitive appreciation for how the reservoir data will affect the amount of oil recovered and economically recoverable from fields.

Water Drive

[illegible] is caused by encroaching water drive, the oil will be displaced by the water. It is evident, the reservoir pressure will remain relatively constant over the producing life of the well. It is obvious that oil is driven the fluids which had previously occupied the pore spaces will be produced until the well turns to water.

The equation for the recoverable production (N) may be simply stated as:

$$N = \frac{\text{volume of gas or}}{\text{production until well turns to water}}$$

Since K is directly proportional to the permeability, if the permeability is reduced the productivity will be reduced in the same proportion. If we assume the water saturation of the water drive to be more or less constant and the reduction in K is at the outside rate, the productive potential will be the same although the productive flow will be increased in the immediate vicinity of the permeability change.

Effect on the Curve

The production vs. water cut curve is plotted by the engineer as the producing interval is cut and tested as the reservoir pressure drops (or if new completions). It is found that as production increases, the production rate will drop off in the form of a definite curve. Typical for most types of these curves are: (a) the maximum rate, (b) the initial decline rate, (c) the load factor. It should be noted that the production decline will follow a mathematical curve only when there are no outside influences of variable pressure from the time the well starts production.

The following example is taken on a type of load-factor decline which is typical in the Mississippian trend:

$$Q = \sum_{n=1}^{n} (1-r)^{n} \qquad (1)$$

$$L = \frac{1}{n} \sum_{n=1}^{n} (1-r) \qquad (2)$$

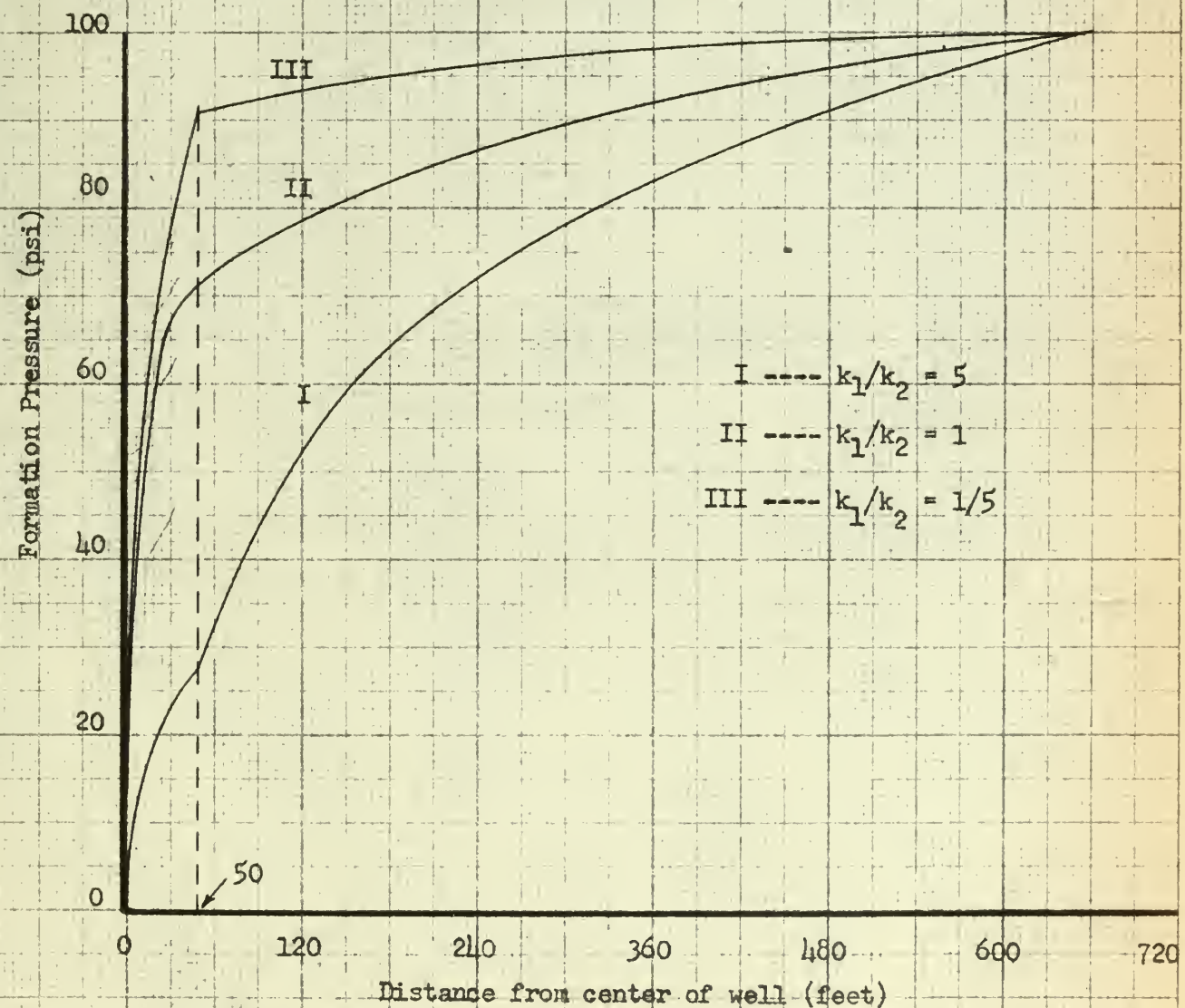
$$L = \frac{\text{average daily production}}{\text{maximum daily production}} \qquad (3)$$

The values of (r) used will be based on the previous information in Section IV, p. 2 wherein (r) or 12% per year and an estimated production rate limit of 5 barrels will be assumed.

Variable: One well has a reservoir permeability of 10.0 md and one foot from the well bore, permeability of approximately 5.0 md would

PRESSURE DISTRIBUTION FROM THE WELL TO THE OUTER BOUNDARY OF THE DRAINAGE AREA

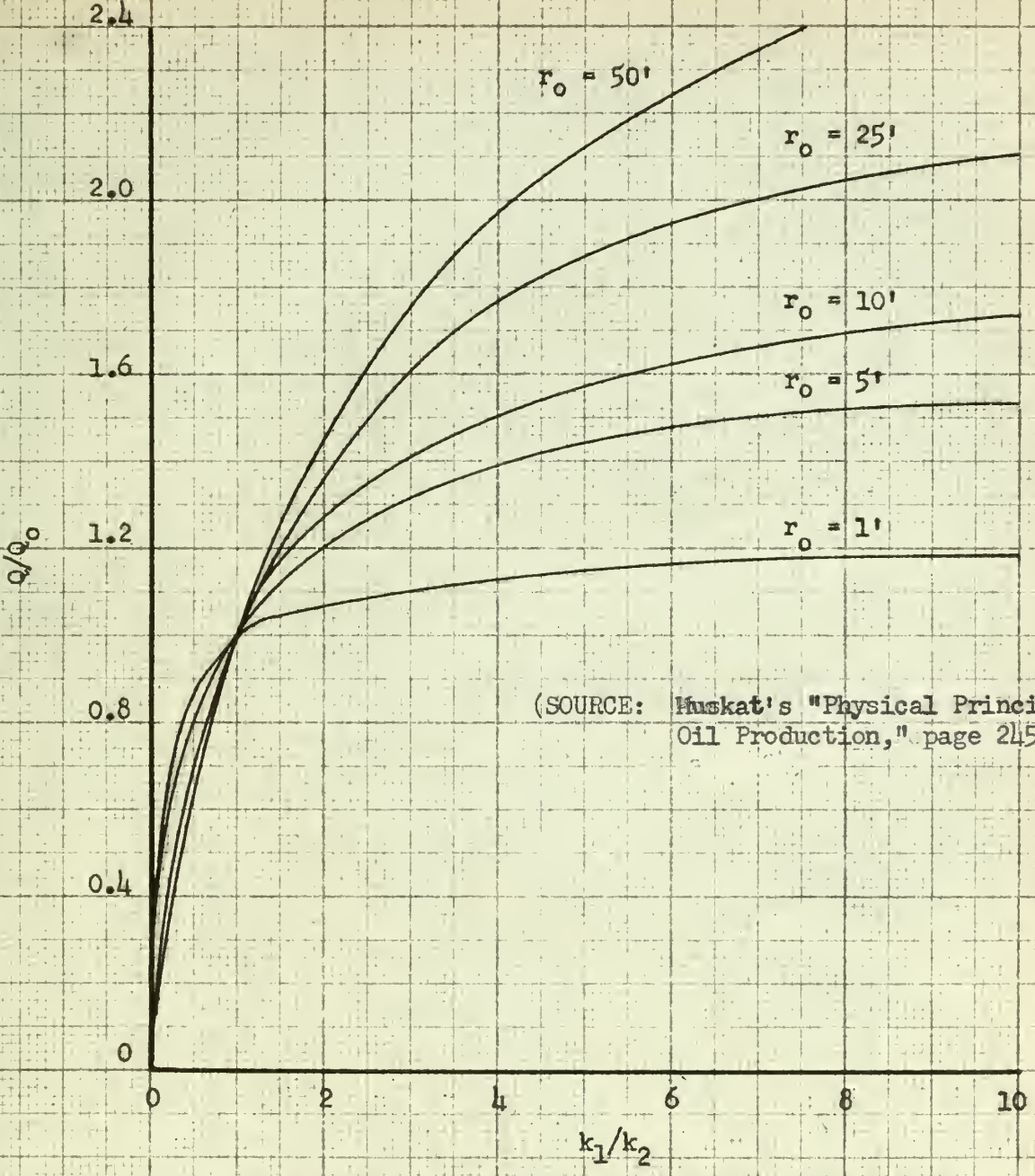
(SOURCE: Muskat's "Physical Principles of Oil Production," page 244)



k_1 = Permeability of damaged section
k_2 = Permeability of undamaged section
r_o = 50 feet r_w = $\frac{1}{4}$ foot
r_e = 660 feet p_w = 0 p_e = 100 psi

FIGURE 1

PRODUCTIVITY INCREASE FOR DAMAGED
OR ACIDIZED SECTIONS

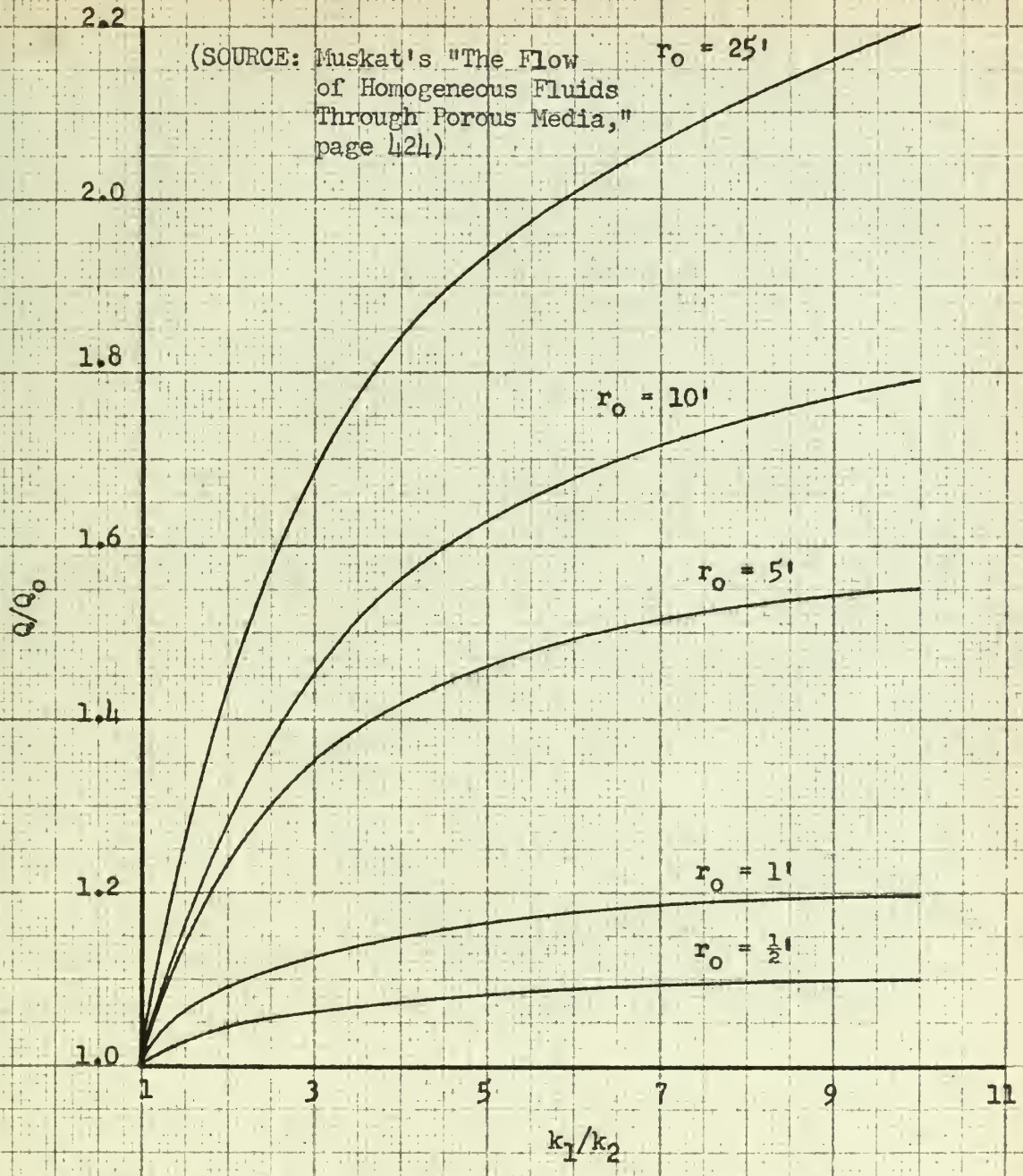


(SOURCE: Muskat's "Physical Principles of Oil Production," page 245)

Q = Production rate with damaged or acidized sections
Q_o = Production rate for undamaged section
k_1 = Permeability of damaged (or acidized) section
k_2 = Permeability of undamaged section
r_w = $\frac{1}{4}$ foot
r_e = 660 feet

FIGURE 2

PRODUCTIVITY INCREASE DUE TO ACIDIZATION IF
THE INITIAL PERMEABILITY IS EVERYWHERE UNIFORM



Q = Production capacity after acidization
Q_o = Production capacity before acidization
k_1 = Permeability of acidized zone of radius (r_o)
k_2 = Permeability of acidized zone before acidization
r_w = ¼ foot
r_e = 500 feet

FIGURE 3

PRODUCTIVITY INCREASE DUE TO ACIDIZATION IF INITIAL PERMEABILITY AROUND THE WELL BORE IS RAISED TO FORMATION PERMEABILITY

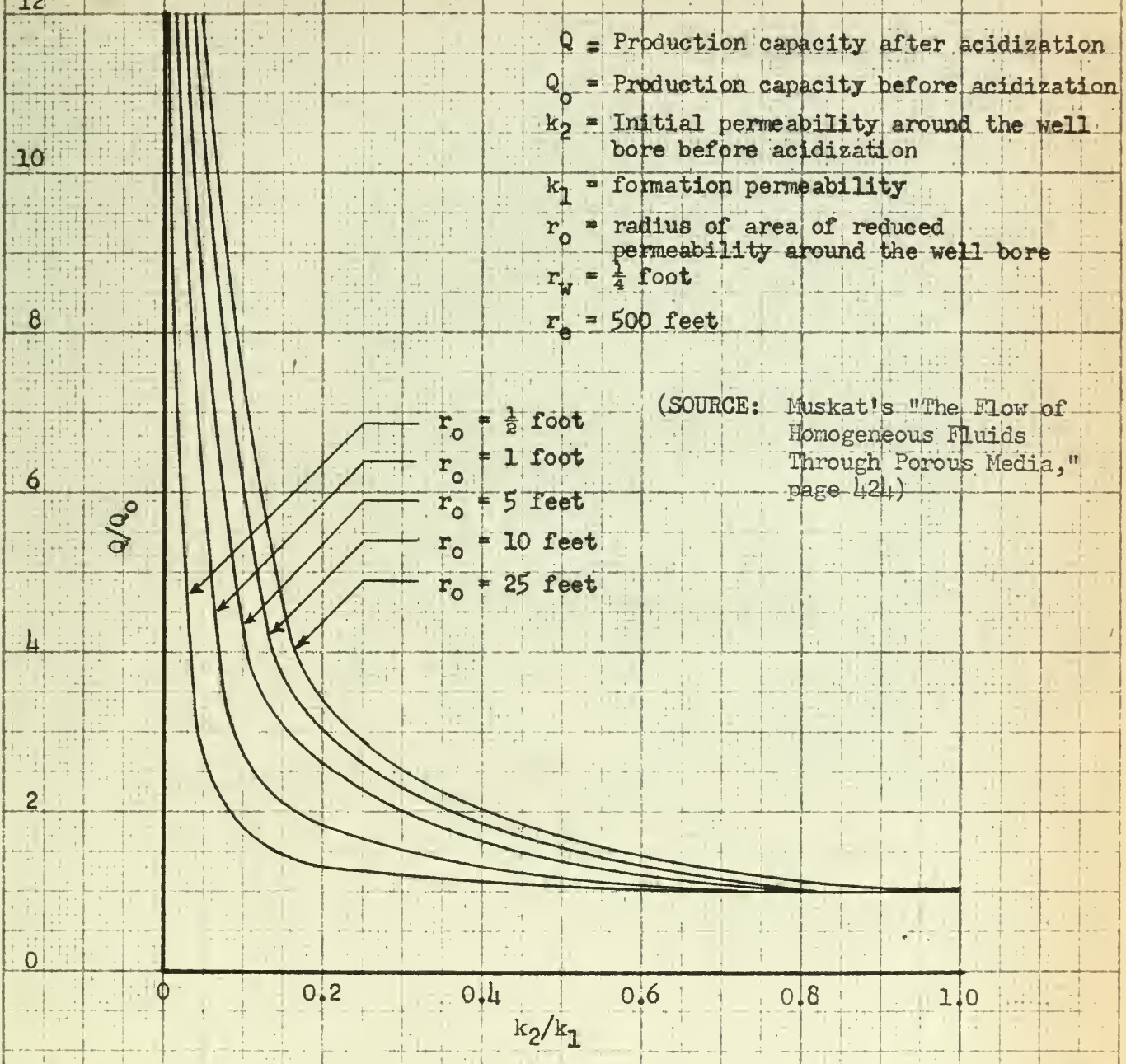


FIGURE 4

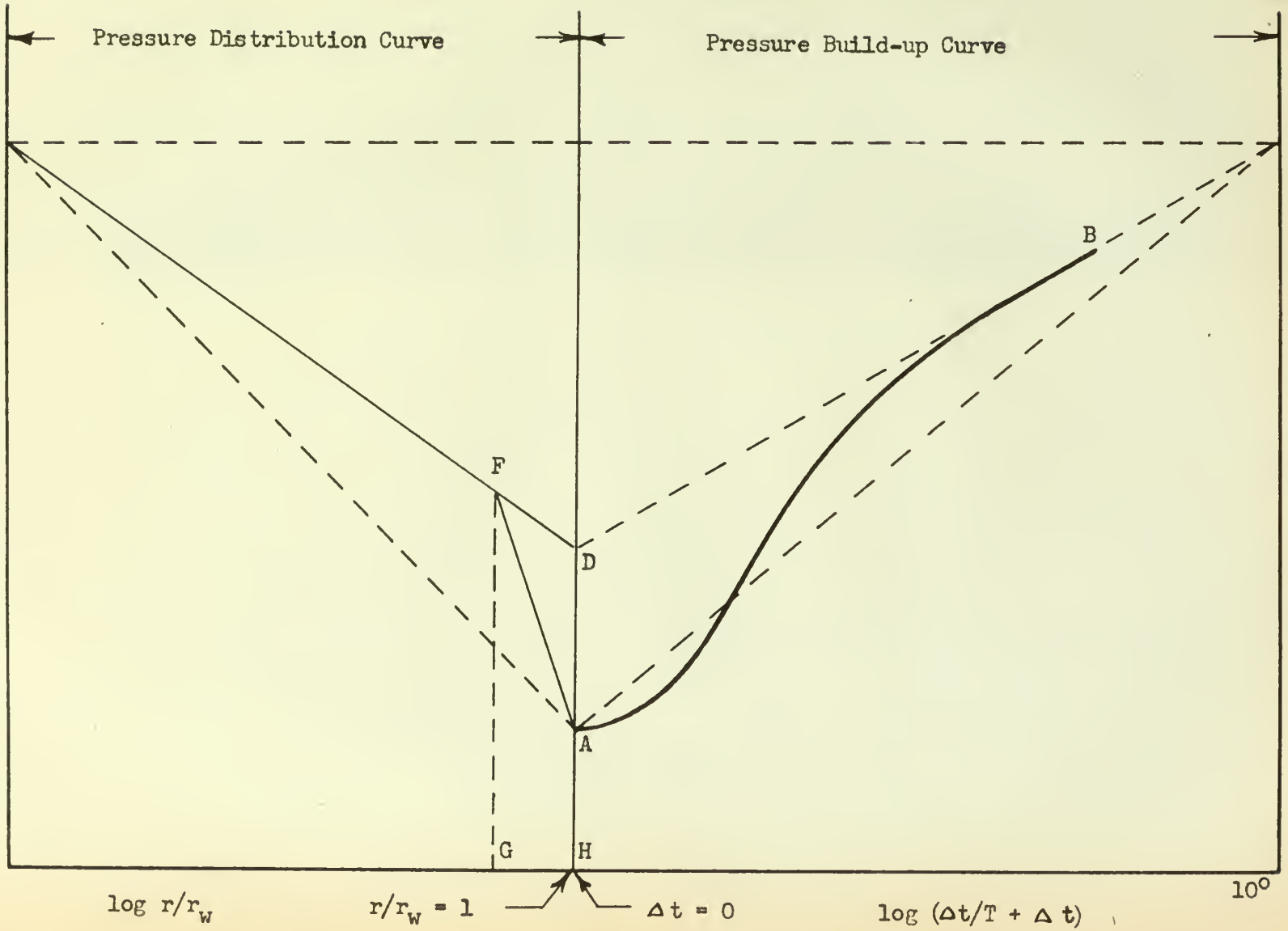


FIGURE 6

DETERMINATION OF AVERAGE FORMATION PERMEABILITY

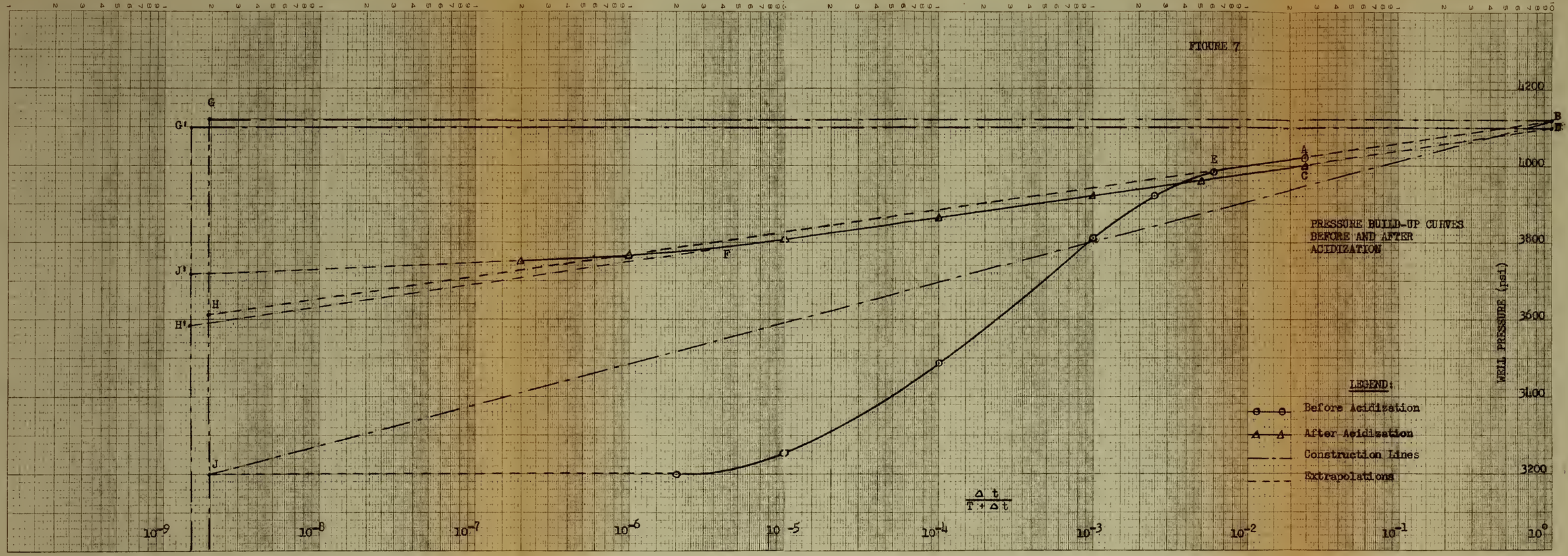


FIGURE 7
PRESSURE BUILD-UP CURVES
BEFORE AND AFTER
ACIDIZATION
LEGEND:
Before Acidization
After Acidization
Construction Lines
Extrapolations
WELL PRESSURE (psi)
4200
4000
3800
3600
3400
3200
G
G'
J'
H
H'
J
F
E
A
C
B
D
$\frac{\Delta t}{T + \Delta t}$
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

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